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New Method of Making Tensile Tests.

A NEW method of testing the tensile strength of concrete, in which 16 in. by 4 in. cylinders are used and the load applied at both ends through threaded rods embedded in rich mortar, is described by Messrs. L. Schuman and J. Tucker in Research Paper No. 1552 of the United States National Bureau of Standards. The authors state that tensile tests of concrete have been made by a number of different methods. The dimensions of the specimens have ranged from 12 in. to 39 in. in length, and from 3 in. to 6 in. square or in diameter. The shapes of the specimens have also varied, depending on the method of applying the load. Some investigators used specimens with enlarged ends to which grips were applied. Others cast cylindrical specimens and used grips clamped or wedged to the ends of the test pieces. Besides the use of unduly large specimens, some of these methods are open to objection because of the way the specimens break. Specimens with enlarged ends often break at the junction of the enlarged and reduced portions. Cylindrical specimens, on the other hand, may break near or within the grips.

The new type of specimen and method of loading are believed to overcome these objections. In principle, the method is similar to that used in the tests of Talbot and of Withey. The new feature is the application of the load to the concrete under test through threaded rods embedded in a rich mortar moulded on the ends of the cylindrical test specimens (*Fig.* 1). The preliminary tests with this method showed that the specimens always broke well within the concrete, and that a bond stress of 700 lb. per square inch of embedded rod area could be safely used. Thus, for the rods in *Fig.* 1, giving about 12 sq. in. of bond area, no failure in bond or at the ends of the rods will occur for loads up to 8,000 lb., equivalent to a tensile stress in the concrete of 600 lb. per square inch.

A few tests were made to compare the new method with certain of the older methods. With a 1 : 4·5 concrete, six specimens were moulded and tested by the new method and six by each of the following methods :

(1) Specimens 4½ in. in diameter, with splayed ends ; space between grips and specimens filled with a plastic material.

(2) Specimens 3 in. in diameter, plain rods of unequal lengths embedded directly in the ends of the concrete ; load applied through plates attached to the rods at each end of the specimen.

By method (1) the values of tensile strength obtained ranged from 350 to 420 lb. per square inch, with an average of 380 lb. per square inch.

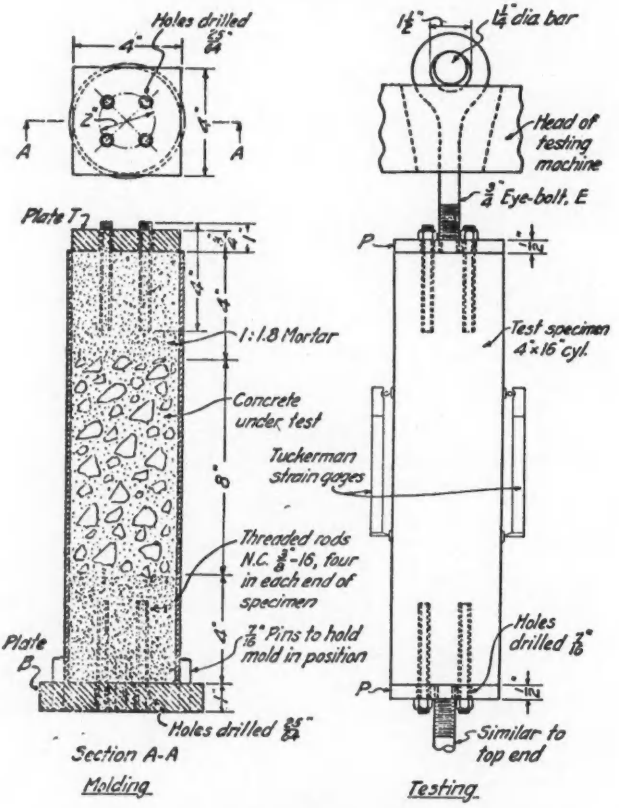

Fig. 1.—New Method of Making Tensile Tests.

By method (2) the values ranged from 245 to 380 lb. per square inch, with an average of 320 lb. per square inch. The values obtained by the new method ranged from 400 to 420 lb. per square inch, with an average of 430 lb. per square inch. The higher value obtained by the new method is believed to indicate a more uniform stress distribution across the section of failure than with the other methods.

A 1 : 3 mortar made with standard sand was also tested. Mortar from the same batch was moulded into standard briquettes and into cylinders of the type used for the new method. At seven days the average strength for three briquettes was 295 lb. per square inch, and for three cylinders, 360 lb. per square inch. At 28 days the averages were 415 and 565 lb. per square inch, respectively.' The cylinders thus gave 22 and 36 per cent. higher strengths than the briquettes.

Materials and Tests.

The cements used in the tests were five normal Portland cements, including a white Portland, four moderate-heat Portland cements, three high-early-strength Portland cements, two Portland-pozzolana cements, one high-alumina cement, and eight Portland cements with resin, tallow, or vinsol resin as aerating agents ground in at the mill. One cement was tested both without and with a soluble aerating agent (sodium lauryl sulphate) added in the laboratory, so that a comparison could be obtained between aerated and unaerated concretes for the same cement.

The aggregates were river sand and gravel ; the maximum size of the gravel was $\frac{3}{4}$ in. For all but the aerated concretes, two mixes were tested with each of the cements (a) 1 : 2·4 : 3·6 by weight and (b) 1 : 1·75 : 2·75 by weight. Only mix (a) was used in the tests on aerated concretes. Compressive and tensile specimens, in triplicate, were made for test at three, seven, and 28 days, three months, and one year, except that for the high-early-strength and high-alumina cements tests at one day were added and the three-month compressive tests omitted. In addition to the compressive and tensile tests, stress-strain relations were determined on the concretes made with the cements containing aerating agents.

To study the effect of varying the proportions, a series of tensile tests was made in which the sand : gravel ratio in a 1 : 6 mix was varied. These tests were made with each of three different Portland cements. The proportions varied from 1 : 1·9 : 4·1 to 1 : 3·4 : 2·6, and the water content was varied correspondingly to maintain approximately equal flow values. Tensile strengths at 3 and 28 days were determined.

Tests were made to study the effect of a few different coarse aggregates. For this series, a single cement with river sand was used. The coarse aggregates were river gravel, limestone, slag, a trap-rock, and granite. Two mixes were tested, except for the granite and trap-rock, for which there was only sufficient material for one mix. For the river gravel, the mixes were 1 : 2·4 : 3·6 and 1 : 1·75 : 2·75. For the other coarse aggregates, the cement-sand ratios were the same, but the proportions of coarse aggregate were varied with the bulk specific gravities so as to give approximately equal yields of concrete. The water contents were varied to give equal flow values, except in one case where the river gravel was tested in a mix with the same cement-water ratio as was used for the other aggregates. Tests were made on the 1 : 6 mixes at seven and 28 days, and on the 1 : 4·5 mixes at three and 28 days. Three specimens were tested at each age.

Preparation of Specimens.

The 6 in. by 12 in. compression cylinders were prepared by A.S.T.M. method C39–39. The mixing time was generally two minutes. Cements containing

aerating agents were mixed for three minutes. The cement-water ratio was generally 1·66 for the 1·6 mix and 2·05 for the 1 : 4·5 mix, but was varied to maintain approximately equal flows. The method of moulding the tensile-test specimens is shown in Fig. 1. The $\frac{3}{8}$ in. by 4 in. threaded rods were held in position by the holes in the bottom plate, *B*, and the mould was held in place by the pins in the plate. The mortar for the ends of the specimens consisted of the test cement and sand, 1 : 1·8 by weight, with a cement-water ratio of 2·4 to 2·6. The lower ends of the specimens were then moulded by rodding the mortar, in two layers, each about 2 in. in depth, so as to extend about 1 in. above the ends of the threaded rods. Concrete was then placed in the mould in two 4 in. layers, each rodded with 20 strokes of the tamping rod. The remaining mortar was then placed and rodded into the top of each mould. The plates *T* were then placed in position over the tops of the moulds and the threaded rods inserted through the holes, with some turning and vertical motion to secure good bond to the mortar. The rods extended 1 in. beyond each end of the specimen to provide for the plates used in testing, and had a length of 3 in. embedded in the mortar. The space between the ends of the rods and the concrete contained a mixture of mortar and concrete. The threaded rods were lightly greased before moulding, and could be readily removed by splitting the cylinders. The same rods were then used in other specimens.

Test Methods.

The compressive tests were made in a 300,000-lb. hydraulic machine at a rate of loading of 1,000 lb. per square inch per minute. The tensile tests were made in a 100,000-lb. beam-and-poise screw-driven machine, operating at an idle head speed of 0·05 in. per minute. Half-inch plates (*P*) were attached to the specimen, and eyebolts (*E*) attached to the plates. The loads were applied through bars passing through the eye of each bolt and resting against the testing-machine heads.

Strains were measured with two Tuckerman optical strain gauges, extended to a 6-in. gauge length. The gauges were seated on thin brass plates attached with plaster of paris to the specimen, and were diametrically opposite each other. An initial stress of 50 or 100 lb. per square inch for the compressive specimens, or of 10 lb. per square inch for the tensile specimens, was applied for the first readings. Rates of loading were the same as for the strength tests, but the loads were maintained as nearly constant as possible while the gauges were being read. Strains were measured to less than one-millionth.

However, because of the difficulty of maintaining constant loads with the hydraulic machine, any load increment may be in error by as much as 400 lb., equivalent to 14 lb. per square inch on a 6-in. by 12-in. cylinder, corresponding to a strain error of $4 = 10^{-6}$ for a modulus of $3{\cdot}5 = 10^{6}$ lb. per square inch. This error is less than 2 per cent. of the strain at a stress of 1,000 lb. per square inch, and correspondingly lower at higher stresses.

Test Results.

For any one specimen of a set of three, the deviation from the average was usually less than 10 per cent. both for the tensile and compressive specimens.

Practically none of the tensile fractures occurred at a distance of less than 2 in. from the ends of the threaded rods, and about 80 per cent. of the fractures were within 2 in. of the middle of the specimen. There was sometimes considerable variation in strength for different cements within a type, as, for instance, for the two Portland-pozzolana cements. However, for both the normal and the high-early-strength Portland cements the variation of either compressive or tensile strength from the average for the type was, at any age, less than 16 per cent. Somewhat greater variation was found among the moderate-heat cements. The aerated concretes also showed considerable variation, as was to be expected from the effect of the various aerating agents on the density of concrete. This varied from 138 to 144 lb. compared with 146 lb. for unaerated concrete.

For both mixes the strengths for the high-early-strength cements, both in tension and compression, for ages up to and including 28 days are higher than for all others, except for the 1 : 4·5 mix with high-alumina cement. To attain an average compressive strength of 4,600 lb. per square inch requires about 28 days for the normal cements, 1 : 6 mix, and about 12 days for high-early-strength cements in the same mix. Similarly, for an average tensile strength of 400 lb. per square inch, attained by the normal cements in 28 days, only about six days are required by the high-early-strength cements. A similar relation applies to the 1 : 4·5 mix. Thus, it appears that the use of a high-early-strength cement is of greater advantage in securing high early tensile than high early compressive strength.

For both the 1 : 6 and 1 : 4·5 mixes, the moderate-heat cements gave strengths up to about 28 days somewhat lower than those for the normal cements. After three days there is a tendency for the moderate-heat cements to give slightly higher strengths, both in tension and compression, than the normal cements.

The aerated concretes, represented only by the 1 : 6 mix, show a wider range of strengths than the other types, as is to be expected both from the variety of aerating agents used and the number of cements tested. Although the tensile strengths at the early ages are on the average slightly higher than those for the normal cements, at the later ages there is a tendency for both tensile and compressive strengths to fall below those for the normal cements.

The two Portland-pozzolana cements differed widely from each other. For one of these, the strengths up to seven days were within the range of those for the moderate-heat Portland cements ; however, after seven days the strengths for this cement were appreciably lower than those given by the moderate-heat cements. The other Portland-pozzolana cement gave relatively low strengths only up to three or seven days, but thereafter the strengths were within the range of those for the normal cements.

The high-alumina cement is unique in showing very high early strength (at three days or less). However, compressive strengths began retrogressing some time after 28 days and tensile strengths some time after three days for the 1 : 6 mix and seven days for the 1 : 4·5 mix, so that at one year the strengths for this cement, both in tension and compression, were no higher than at one day, and were less than for any other type of cement.

While the concretes made with two of the three high-early-strength cements showed slight retrogression in compressive strength for the 1 : 6 mix after 28 days, those made with all the other types of cement except the high-alumina showed continued increase in compressive strength, for both mixes, up to a year. Tensile strengths, however, usually reached a maximum value at some time between seven days and three months, followed by retrogression. The maximum tensile strengths obtained for the 1 : 6 mix with the high-early-strength cements were higher than those for the same mix with the other cements. However, the high-early-strength cements showed relatively large retrogressions and, at three months and thereafter, gave about the same tensile strengths as the normal cements. For the 1 : 4·5 mix, two of the three high-early-strength cements gave maximum values at seven days, but these were no higher than those attained by other cements at later ages.

The average strengths for the moderate-heat cements at one year were the highest for all cements tested. For the normal and Portland-pozzolana cements, any retrogression between 28 days and three months was usually followed by some recovery, so that, at one year, the tensile strengths are never more than 10 per cent. lower than at 28 days, and are often higher.

The retrogressions in tensile strengths of concretes after certain ages may be due to retrogression in mortar tensile strengths, since such retrogression occurs with mortar briquettes. The retrogressions may also be due in part to decrease in bond strength between gravel and mortar. Considerable gravel fracture was noted at 28 days, and there was some tendency for the percentage of gravel fractured to decrease with age thereafter.

In general, the concrete with the higher cement content (1 : 4·5 mix) gave higher strength, for all cements, than the 1 : 6 mix, at corresponding ages. However, there are some noteworthy differences between the rates of increase of tensile and of compressive strength. To attain an average compressive strength of 4,600 lb. per square inch requires 28 days for the 1 : 6 mix and about 14 days for the 1 : 4·5 mix. Similarly, the average tensile strength for the 1 : 6 mix was about 400 lb. per square inch at 28 days, and this is attained by the richer concrete in only eight days. There was a similar relation for the two mixes with the high-early-strength cements. Thus the use of the richer mix is of greater advantage in securing high early tensile than high early compressive strength.

For equal compressive strengths, tensile strengths tend to be somewhat higher for the 1 : 4·5 mix than for the 1 : 6. There is also a tendency for the aerated concretes to have higher tensile strengths for equal compressive strengths up to about 2,500 lb. per square inch than the other 1 : 6 concretes. The high-alumina cement shows appreciably lower tensile strength, for equal compressive strengths, than the other cements.

For the compressive specimens the difference in strain values for opposite sides of the same specimen was usually less than 60×10^{-6} for stresses up to three-fourths of the breaking stress; this corresponds to a stress difference of 250 lb. per square inch or less. For the tensile specimens the corresponding difference in

strain values was usually less than 10×10^{-6}, equivalent to a stress difference of 40 lb. per square inch or less. The deviation of the strain for one specimen from the average for a set of three was only about 20×10^{-6} for the compressive tests, and about 3×10^{-6} for the tensile tests.

In general both compressive and tensile moduli increase with increasing compressive strengths and density of concretes. The compressive moduli varied from 3·4 to $4{\cdot}1 \times 10^6$ lb. per square inch, and the tensile moduli varied from 3·3 to $4{\cdot}0 \times 10^6$ lb. per square inch. The tensile moduli show no relation to the tensile strengths. For the same concrete, the tensile modulus appears to be slightly lower than the compressive modulus.

Summary.

(1) The method gave fairly uniform results because of the greater uniformity of stress distribution over the section of failure than is obtained with grips, or in tapered specimens, etc.

(2) Compressive and tensile strengths and some stress-strain relations were determined for concretes made with a number of cements of various types.

(3) The high-early-strength cements gave higher strengths than the normal cements, both in tension and compression, up to 28 days. The moderate-heat cements gave but slightly lower strengths than the normal cements up to 28 days; thereafter there was some tendency for the moderate-heat cements to give higher compressive and tensile strengths than the normal cements. The cements with aerating agents gave somewhat higher tensile strengths than the normal cements up to seven days, but thereafter both compressive and tensile strengths were lower than those for the normal cements. Of the two Portland-pozzolanas tested, one gave rather low early strength but came within the range for the normal cements at later ages; the other gave early strengths comparable with a moderate-heat Portland but gave relatively low strengths at later ages. The high-alumina cement gave very high strengths at one day but showed comparatively little gain at later ages.

(4) Tensile strengths usually attained maximum values between seven days and three months, with retrogression in many cases. However, at one year tensile strengths were generally within 10 per cent. of the 28-day strengths, except for the high-alumina cement which gave appreciably lower values. The fracture sections of the tensile specimens often showed considerable aggregate breakage at 28 days, and somewhat less at later ages.

(5) The 1 : 4·5 mix generally gave higher strengths for all cements than the 1 : 6 mix at the same age. The use of either a richer mix with the normal cements, or of a high-early-strength cement, was of greater advantage in securing high early tensile strength than high early compressive strength.

(6) Tensile and compressive strengths show a fair relation, but the 1 : 4·5 mix gave somewhat higher tensile strengths for equal compressive strengths than the 1 : 6 mix. For compressive strengths up to about 2,500 lb. per square inch, the 1 : 6 aerated concretes gave somewhat higher tensile strengths for equal compressive strengths than the 1 : 6 mix with normal cements. The high-alumina cement

gave appreciably lower tensile strengths for equal compressive strengths than the other cements.

(7) For the nine aerated 1 : 6 concretes tested with river sand and gravel, the weights per cubic foot ranged from 138 lb. to 144 lb. compared with 146 lb. for a corresponding normal cement concrete. Initial tangent moduli of elasticity for the aerated concretes ranged from 3·4 to 3·9 $\times$ 10^6 lb. per square inch in compression, and from 3·3 to 3·8 $\times$ 10^6 lb. per square inch in tension, compared with 4·1 and 4·0, respectively, for a normal cement concrete. Both the tensile and compressive moduli increased with compressive strengths, which ranged from 3,100 to 4,600 lb. per square inch at 28 days.

(8) Tensile strengths of concrete varied considerably with the sand-gravel ratio or with the type of coarse aggregate used. A range of 1·4 to 1 in tensile strength at 28 days was noted for different coarse aggregates, such as slag, crushed stone, and gravel. A crushed limestone gave relatively low tensile strength in a 1 : 6·4 mix, and rather high strength in a 1 : 4·8 mix.

Automatic Control of Rotary Kilns.

THE problem of automatic kiln control has recently been discussed by Mr. John R. Green in papers presented to the American Institute of Mining and Metallurgical Engineers and the American Portland Cement Association. These two papers are summarised by their author in "Rock Products," where it is pointed out that, on the basis of actuating medium, control systems may be divided according to the following classifications: (1) Electric control, (2) Pneumatic control, and (3) Hydraulic control.

Electric control systems involve no control signal transfer lag. The rate of response of the control mechanism is determined by the mechanism speed which is usually constant and fixed regardless of the magnitude of demand. Frequently an intermittent operation, either in the controller or control mechanism, is required. By means of electrical or mechanical devices all types of controls can be supplied with electric operation. Upon interruption of actuating medium the control mechanism normally remains in its last position. When intermediate relays are required between the controller and the mechanisms, additional lag may be introduced. When explosive, contaminating or dirty atmospheres are encountered suitable protection must be provided.

Air-operated controls usually incorporate pilot valves or relays which provide immediate response in the control mechanism and therefore minimise control signal transfer lag. Control is normally continuous rather than intermittent. Power requirements can be handled by the size of diaphragm or piston area in the control mechanism, and positive positioning is assured by position relay devices. All types of control are available in air-operated equipment, and the throttling and automatic reset or rate response type are inherently handled with greater simplicity than by electric control. Upon interruption in the control medium,

air control systems are normally designed to move to the " safe " position. Proper cleaning and preparation of the air supply, occasionally making use of standby or storage units, ensure a continuous and trouble-free supply with a minimum of attention. Explosive atmospheres present no hazard, and contaminating or dirty atmospheres are not troublesome due to the self-purging nature of air control. By the use of " non-bleed " pilot valve construction air is consumed only during valve movement and therefore requires only a minimum air consumption.

Hydraulically-operated controls are similar to air-operated equipment in their characteristics, but normally involve more extensive supply and return systems and have not been built into indicating or recording controllers.

In rotary kiln control, the objectives might be listed in the order of their importance as follows : (1) Uniform high quality of product, (2) Maximum production, (3) Fuel efficiency, and (4) Low maintenance cost. It is obvious that the ultimate in each objective detracts from attaining other desirable conditions; the ultimate in fuel efficiency may, for example, detract from uniform high quality of the final product.

Radiation pyrometers (when properly designed and protected) are adequate for measuring kiln temperatures, particularly where records or automatic control are desired. Optical pyrometers serve well as portable indicating devices. Light sensitive devices, or photoelectric cells, are also applicable to this service, and are capable of producing records as well as certain forms of automatic control. The characteristics of high-temperature measuring devices which are particularly desirable for rotary kiln work might be listed as follows : (1) The dust condition inside the kiln usually fluctuates considerably, and these fluctuations have their effects upon the readings, but are not cumulative and show as a continuous fluctuation in the temperature indicated, provided the radiation unit and recorder are responsive to such slight and rapid temperature fluctuations. (2) Since the surrounding temperature to which the measuring unit is subjected fluctuates from possibly 0 to over 200 deg. F., these changes should have no effect upon the final reading or upon the life of the measuring unit. (3) In order to secure the measurement of temperature as far into the high fire zone as possible, a very narrow sighting angle is desirable. (4) In order to be sure that the proper field is being viewed, it is desirable to have some sighting means on the measuring unit through which the field can be observed.

Kiln and feeder speeds are easily measured by means of electric generator tachometers geared to the drive motors and indicated, recorded, or automatically controlled on the firing floor. Revolutions or production rates are recorded on electrical or mechanical counters. Kiln feed, whether by volume or weight, is usually synchronised with kiln speed by mechanical or electrical interlocking, but it may be automatically controlled in any ratio by means of differential tachometer instruments.

Regulation of fuel to air ratio is desirable to maintain either maximum combustion efficiency or the desired atmospheric conditions inside the kiln. Continuous gas analysis equipment suitable for recording or automatically controlling these conditions have been, however, beset with a multitude of ills. The fact that large

quantities of dust are usually present in the exhaust gases makes the securing of a continuous clean sample, without excessive maintenance, difficult. For the cement and lime industries, the analysis for total combustibles or oxygen, or both, depending upon the desired gas composition, seems to be the logical answer. All continuous gas-analysis equipment should be electrical in principle so that time lag is reduced to the minimum, or at least electrical in transmission since the recorder or controller should always be on the firing floor at a considerable distance from the analysis equipment.

One other method of measuring combustion efficiency has proved practicable where the exit gases are high enough in temperature to support combustion. It consists essentially of making the exit kiln housing and flues into a total combustible meter. In addition to the usual kiln exit temperature element, another element is installed in the duct system or kiln housing following the admission of air, preferably for this purpose and in reasonably constant volume. If unburned combustibles are present, secondary combustion takes place and a higher temperature is shown by the second element. The simplest and most effective way of showing this condition is to connect both elements differentially on a recording meter located on the firing floor, thus eliminating the necessity for reading differences between two recorded temperatures. The trailing element will normally be at a lower temperature due to radiation losses, but when secondary combustion takes place its temperature approaches or exceeds the first element. Bearing in mind that the heat losses caused by the presence of ½ per cent. CO in the flue gas are approximately equal to those found with 20 per cent. excess air, any air deficiency is a serious blow to fuel efficiency as well as such secondary factors as boiler-tube conditions caused by secondary combustion.

There are two basic methods of automatic control. Both involve temperature measurements, but by contrasting methods. The first method consists of maintaining a constant firing rate which will not burn the linings, and automatically varying the kiln speed, charging rate, or both in unison, from the product temperature as it leaves the high fire zone. The advantages claimed for this method are as follows: (1) Maintains steady firing rate with stability in all of the related factors of air volume, air temperature, furnace pressure, etc. (2) Maximum possible firing rate that refractories will stand. (3) Maximum kiln speed or production rate that will produce a properly-fired product under these conditions. One notable disadvantage of this system, which is based upon changes in kiln speed, is its distortion of the time-temperature relationship on the product, and the fact that a large quantity of material in the kiln is affected at one point or another in its heating period, with a corresponding long-time lag in stabilising the final results.

The second method consists of the automatic control of fuel supply from kiln-wall temperature. The primary object of this method is to run the kiln wall in the high temperature zone near the maximum safe temperature which will not damage the lining, the kiln speed (and feed) being held constant at the maximum speed and charging rate to deliver the desired product. This method of operation has the following advantages claimed for it: (1) Comparatively rapid response to

changes, i.e. small process lag. (2) Does not vary the desired time-temperature schedule. (3) Follows the basically sound principle in the automatic control of continuous processes of not varying the production rate if variation of any other factor will produce the desired results. (4) Responds to some extent to changes in the temperature of the product, as caused by minor fluctuations in the mass being discharged, and tends to offset these changes before the product leaves the kiln. A possible disadvantage of this system is the lack of a direct temperature measurement of the product. This can, however, be substituted for the measurement of kiln lining temperature, with the corresponding loss of control over the maximum allowable temperature of the kiln lining.

It is possible to combine both of these basic methods of control, i.e. fuel supply or kiln speed, since they supplement each other, although the stabilisation of a major condition by either method usually permits easy manual regulation of the factor.

Supplementing any basic control plan, a number of the contributing factors to combustion may be controlled, depending upon the mechanical equipment and processing devices used in connection with the kiln proper. Kiln pressure control should be of the differential type, i.e. compensated for atmospheric pressure changes near the pressure tap, and preferably taking its measurement at the firing hood rather than at the feed-end housing in order to compensate for varying kiln resistance, such as is caused by ring formations of the product. The control of primary air volume is readily accomplished, as is also a reasonably accurate control of powdered coal-feed in unit air-swept mills equipped with constant level devices. Temperature control of primary air, where preheated air passing over cooling products is available, is also easily secured by " bleed " dampers. Where a control of primary air volume is not used the installation of face and by-pass dampers rather than a " bleed " damper helps to maintain reasonably uniform volume. The control of secondary (or total) air volume is a controversial subject. Within certain limits, however, it is capable of stabilising conditions.

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The Flow of Heat in Lime Kilns.

A USEFUL explanation of the interchange of heat and the flow of energy in lime kilns is given by Mr. V. J. Azbe in "Rock Products" for May, 1943.

Fig. 1 shows diagrammatically a kiln with three main zones, the preheating, calcining, and cooling zones. In many kilns the cooling zone is nonexistent, particularly in many rotary kilns. The heat in the fuel pours into the kiln as a stream. One of the initial losses from this stream is that of latent heat vapour, due to the combustion of hydrogen to form water. Natural gas may have a heat content of 100 B.T.U., but it is a high hydrogen fuel and so about 10 per cent. of the heat becomes latent. This heat, so far as a lime kiln is concerned, is so completely unavailable that in the diagram it is deducted before the main energy stream enters the kiln. With coal, which is a fuel of lower hydrogen content, the loss due to latent heat is only about 5 per cent.; with wood it is high, and with coke very low.

Another stream deducted from the main flow before it enters the kiln is that due to incomplete combustion. While during incomplete combustion of carbon to carbon monoxide some heat is developed, this heat in the case of a lime kiln is ineffective; so also may be considered that part of the fuel incompletely burned and totally wasted. It should be noted that the main stream is divided into two portions, that of low-intensity heat and that of high-intensity heat. One is the portion below the dissociation temperature of calcium carbonate, the other that above it. As the dissociation point varies with CO_2 concentration the precise division point cannot be stated, but we may assume it to be as low as 1,600 deg. F.

High-intensity heat will make lime and low-intensity heat will not; that is, not directly and not until it has been regenerated or reconverted to the high-intensity form. All kilns have more low-intensity heat than is needed for preheating the limestone, and insufficient heat of high intensity. Thus a heat loss from the high-intensity stream is far more serious than loss of heat from the low-intensity stream. *Fig.* 1 shows one small stream departing from the high-intensity portion and passing out of the kiln. This represents the heat radiated from the hot zone, and includes not only that from the calcining zone of the kiln proper, but also that of the furnace, gas flues, and even the gas producer if one is used. This lost portion would all have been available for lime making. The balance of the heat in a good kiln all goes to making lime and to heating the lime from the preheating zone temperature to that of the hot zone. As sensible heat of chemically entrapped energy it turns down into the cooler.

The heat of lower intensity turns towards the preheating zone of disssociate magnesium carbonate, if any, and to preheat the stone. The supposition is that combustion is complete in the hot zone and that no unburned gases escape into the preheating zone, for if this takes place preheating is by high-intensity heat and the waste is very great. That is what takes place in many rotary kilns, and to such a great extent that virtually all preheating is by heat that should have

been utilised in calcining the rock, all due to imperfect combustion control arrangements.

At this stage to simplify the picture it will be assumed that the gases pass into the preheating zone without a temperature head and are completely burned; further, that there is no magnesia present, so there is only the heat of low intensity whose sole duty is preheating the calcium carbonate ($CaCO_3$) with its attendant impurities. *Fig.* 2 is a continuation of the imperfectly developed *Fig.* 1. It elaborates on the preheating process and later influences from preheating.

Calcium carbonate is preheated as such, but the heats imparted to its two components, CaO and CO_2, are to have different histories. As it is shown, the heat of preheating the CO_2 portion is reverted to the upflowing heat stream when

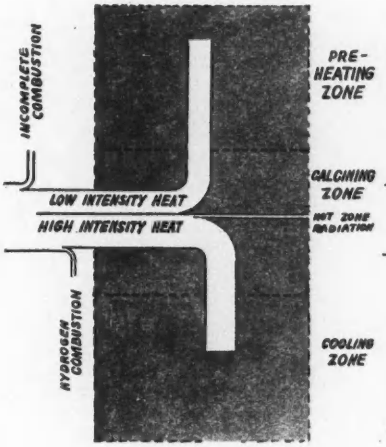


Fig. 1.

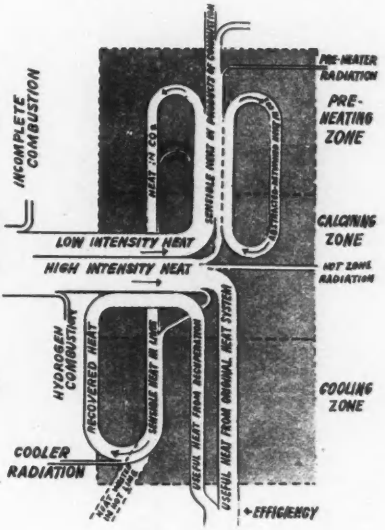


Fig. 2.

dissociation takes place, and the escaping CO_2 joins the upflowing products of combustion. Thus this portion of the heat virtually circulates in the kiln in a closed circuit. What is absorbed from the heat stream in the preheating zone is returned to it in the hot zone and balances the other. The heat of the escaping CO_2 from one batch of lime preheats the CO_2 in the stone of another batch of stone, so that the heat of CO_2 preheating, once the flow is established, becomes a separate entity, and the low-intensity stream coming up the kiln is utilisable only for the preheating of the CaO portion of the stone plus the impurities, as well as the little necessary to drive out the moisture. The heat of preheating the CaO portion of limestone, as well as that imparted to impurities, or what is to be

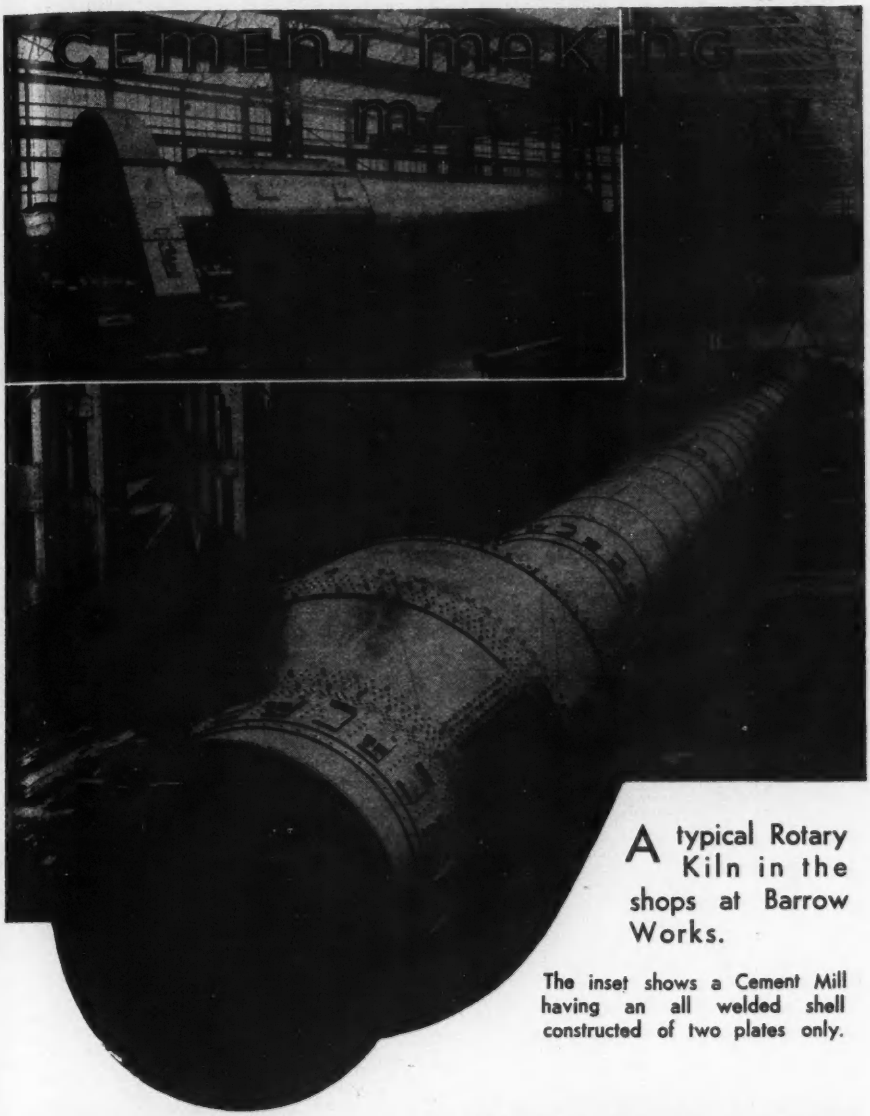
core, plays a far more important part and may be responsible for efficient or inefficient operation, all depending upon which way the stream is directed.

In the upper parts of the kiln, as shown by *Fig.* 2, the stream of heat energy starts downward, grows, and is enriched by sensible heat abstracted by the impurities. It is further enriched from the stream of high-intensity heat as the lime passes through the hot zone, so that it is quite a substantial stream when it reaches the cooler. As indicated in *Fig.* 2, it is recovered ; or it may be wasted, as shown by dotted lines. If the lime is drawn hot, its sensible heat is lost through cooler wall radiation. It can be utilised to preheat air for combustion. In the latter case this heat stream is reversed and brought back into the hot zone as part of the high-intensity stream. If it is so brought back, the kiln efficiency is raised by about one-third. If the air necessary for combustion is not heated to hot-zone temperature with sensible heat from the lime, it will be heated from the high-intensity portion of the main stream, thus greatly lessening the amount available for the calcining process.

Fig. 2 also shows what goes on in the upper kiln section. A small radiation loss from the heat stream deviates, but that is not very serious, since its origin is the low-intensity main stream containing more heat than can be utilised. Then at the top two more heat streams pass to waste, the first constituting the remaining sensible heat of products of combustion, such as could not be utilised in the process of preheating the stone, not necessarily because there was not enough stone but rather because there was not enough stone passing down the kiln in proportion to heat passing up the kiln.

It is not the height of the kiln that determines the exit-gas temperature and heat content, but rather the efficiency of the hot zone in conserving heat of high intensity for purposes of calcination. For example, if by complete recovery of sensible heat in the lime the ratio of lime to fuel is increased by one-third, then one-third more stone comes down the kiln and the escaping gases will be cooled by that much and the escaping heat stream reduced.

That, however, is not the case with the second heat stream departing at the top, that of heat carried to waste by excess air. Much depends on where the excess air enters the kiln. If it enters in the upper kiln section, the heat it contains is of no great consequence, being what might be termed "spent heat." If, however, it enters anywhere in the hot zone section the matter is serious ; and if the excess air is much the loss may be very great. Thus 100 per cent. excess air used for burning of fuel will reduce the fuel ratio by a minimum of half if the cooler is not functioning as a recuperator. In *Fig.* 2 the excess-air heat stream originates in the hot zone from the high-intensity portion and passes up and out to direct waste. With this loss the remainder of high-intensity heat is less and so lime-making capacity is correspondingly reduced. Heat loss from excess air is as serious, or even more so, than that caused by incomplete combustion. In one case the potential energy is not converted into heat ; in the other it is, but it is wasted. Some excess air is needed to ensure complete combustion, but in properly designed and operated kilns this is not much. This applies to both vertical and rotary kilns.



A typical Rotary Kiln in the shops at Barrow Works.

The inset shows a Cement Mill having an all welded shell constructed of two plates only.

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Combustion should be complete before the gases enter the preheating zone, and it is really the junction between the calcining and preheating zones from which the gases should be withdrawn for analyses for determination of their oxygen and carbon monoxide contents.

Fig. 3 shows a still further developed diagram. In essentials it is very much the same as *Fig.* 2 except that the magnesia (MgO) zone is added. This zone is distinctly separate from the CaO zone of a kiln, for the initial dissociation points of the two carbonates are 500 deg. F. apart, being lower for magnesia. Here a third stream of physical heat is converted into chemical energy coming down the kiln, that of MgO. In addition, the sensible heat stream is also much greater because it is enlarged by the sensible heat portion of the high specific heat of MgO. To the extent represented by this 500 deg. dissociation temperature difference, plus the preheating effect of MgO, heat is taken from the gases of the calcium kiln proper; and only for the additional difference does the magnesia zone draw on the high-intensity stream.

So it can be seen why the dolomite kiln, because of the economising effect of the magnesia zone, should have a much higher lime-to-fuel ratio than the high-calcium lime kiln; yet ordinarily the ratios are inferior. Although additional quantities of heat are recovered by the magnesia zone, greater quantities are wasted by incomplete combustion, excess air streams, and failure to recirculate back into the hot section of the kiln the sensible heat of the lime.

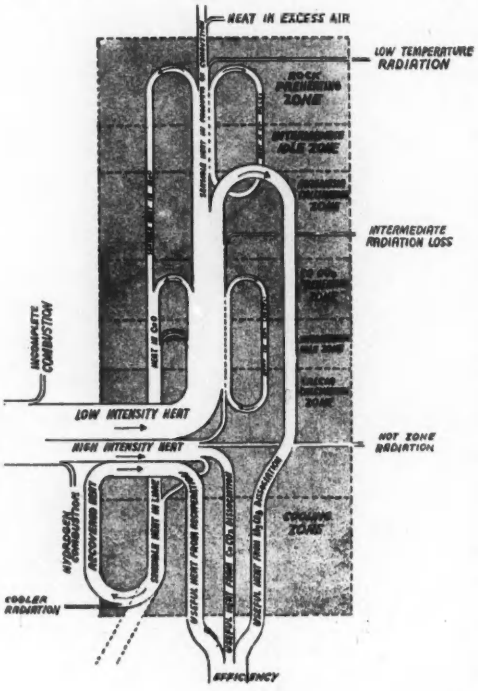

Fig. 3.

Fig. 3 is divided into five main zones: initial preheating, magnesia calcination, calcia (CaO) preheating, calcia calcination, and cooling zone. In addition there are two intermediate zones which have not been mentioned. These are not found in old-fashioned kilns, nor in kilns now driven at high capacities. In low-capacity kilns they may take up much of the height. These intermediate zones are where stone preheated to the gas temperature is held there for the time being with no interchange of heat.